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Preferential Flow Path Effects on Subsurface Contaminant Transport in Alluvial Floodplains

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Abstract. *For strongly sorbing contaminants, transport from upland areas to surface water systems is typically considered to be due to surface runoff with subsurface transport assumed negligible. However, certain local conditions can lead to an environment where subsurface transport to streams may be significant, a source of contamination not alleviated by current best management practices (e.g. riparian buffers). The Ozark region, including parts of Oklahoma, Arkansas, and Missouri, is characterized by cherty, gravelly soils and gravel bed streams. Previous research identified a preferential flow path (PFP) at a field site along the Barren Fork Creek in northeastern Oklahoma. With the subsoils having hydraulic conductivities on the order of 100 to 500 m/d, the previous research demonstrated that even a sorbing contaminant such as phosphorus can be transported in significant quantities through the subsurface. The objective of the current project was to determine the connectivity of the PFP to the stream and to further evaluate the hypothesis that the alluvial groundwater acts as a transient storage zone, providing a contaminant sink during high flow and a contaminant source during baseflow. A trench was installed above the PFP with the bottom of the trench at the topsoil/alluvial gravel interface. Piezometers were installed along the PFP and throughout the riparian floodplain, which was mapped with electrical resistivity equipment. Water was pumped into the trench to maintain a constant head, and a conservative tracer (Rhodamine WT) was injected into the trench. Water table elevations were recorded real-time using water level loggers and water samples were collected throughout the experiment. Results of the experiment demonstrated preferential movement of Rhodamine WT along the perched preferential flow pathway, infiltration of Rhodamine WT into the alluvial groundwater system, and then transport in the alluvial system as influenced by the stream/aquifer dynamics. This research demonstrated the importance of physical heterogeneity in affecting contaminant transport even in coarse gravel, alluvial subsoils.*

Keywords. Subsurface Transport, Non-point Source Pollution, Alluvial Groundwater, Floodplain Management, Ozark Region

Introduction

The adverse impact of increased nutrient loads on surface water quality has drawn considerable attention in recent years. Polluted drinking water, excessive algal growth, taste and odor issues, and fish kills are only a few of the negative effects that can result from an overload of nutrients. In order to protect and enhance drinking water systems, recreation activities, and aquatic ecosystems, water scientists need to identify critical nutrient source areas and transport mechanisms within a catchment. While nitrogen is a concern, phosphorus (P) is generally considered the most limiting nutrient in most surface water systems (Daniel et al., 1998). Excessive soil P concentrations can increase potential P transport to surface waters or leaching into the groundwater, resulting in negative consequences.

Countries throughout the world have spent billions of dollars installing riparian buffer zones adjacent to stream systems to prevent sediment, nutrient, and pesticide transport to streams from land use practices in riparian floodplains. Because buffers primarily address the commonly observed and more easily understood runoff transport mechanism (Lacas et al., 2005; Popov et al., 2005; Reichenberger et al., 2007; Poletika et al., 2009; Sabbagh et al., 2009), effectiveness becomes an issue if a transport pathway through the subsurface circumvents the surface trapping objectives of the riparian buffer (Cooper et al., 1995; Lacas et al., 2005). Local or regional conditions can lead to conditions where subsurface transport may be important (Turner and Haygarth, 2000; Lacas et al., 2005; Fuchs et al., 2009). For example, sources of P from the Illinois River basin to Lake Tenkiller, located in northeastern Oklahoma and northwestern Arkansas, are estimated to be 35% from point sources, 15% from poultry litter application and

50% from other nonpoint sources (Storm et al., 2006). Data suggest that groundwater mechanisms may play an important role in P fate and transport in the Illinois River basin. There is a statistically significant (α=0.5) correlation between base flow P concentrations and poultry house density in nonpoint source impacted streams in the Illinois River basin. This research hypothesizes that this correlation is a result of alluvial deposits providing a transient storage zone during high flow events with elevated P concentrations, and connectivity between P in surface runoff and shallow groundwater.

A study by Fuchs et al. (2009) in northeastern Oklahoma demonstrated at one field site along the Barren Fork Creek that subsurface transport of P is significant in localized preferential flow paths (PFPs). These high velocity pathways transported P at the same concentrations as that applied to the system. Non-preferential flow pathways appeared to adsorb added P from the water and retard P movement. Also, background P concentrations in the preferential flow paths were significantly higher than background P concentrations in non-preferential flow paths, suggesting that a P transport connection exists between the preferential flow paths and the stream and/or upland areas. However, this research was limited to monitoring flow and transport pathways of less than 3 m from the trench for the PFP and 5 to 7 m from the trench for nonpreferential flow paths.

The objectives of this research were: 1) to determine the connectivity of the PFP to the stream using subsurface mapping techniques, 2) to document the movement of a conservative tracer (i.e., Rhodamine WT) along the mapped PFP and in areas surrounding the PFP, and 3) to further evaluate the hypothesis that the alluvial groundwater acts as a transient storage zone, providing a contaminant sink during high flow and a contaminant source during baseflow. This research aimed to demonstrate the importance of physical heterogeneity in affecting contaminant transport even in coarse gravel, alluvial subsoils.

Materials and Methods

Subsurface Mapping of the Riparian Floodplain

The subsurface of the alluvial floodplain at the Barren Fork site was mapped using two methods of electrical resistivity and a high-precision base station global positioning system (GPS). General wide-scale mapping was accomplished with the Geometrics “OhmMapper”, a capacitively-coupled, A-C “dipole-dipole” system, and more detailed imaging was performed with an Advanced Geosciences, Inc. “Super Sting” DC resistivity meter (ERI) (Pellerin and Alumbaugh, 1997; Pellerin, 2002; Poole et al., 1997; McCorley et al., 2003; Robinson et al., 2008). The OhmMapper system consisted of a transmitter dipole and 5 receiver dipoles each 5 m long with a transmitter-receiver offset (rope length) of 10 m. This produced an array 40 m long towed by an ATV mounted with a high precision GPS receiver, providing data for a 5 m maximum depth into the soil profile.

The ERI uses 56 electrodes placed at a spacing ranging from 1 to 2.5 m producing data to a depth of 13 to 20 m, respectively. Additionally, the proprietary data collection routines and software allow increased image resolution (Halihan et al., 2005). The GPS was a TOPCON HiperLite Plus, configured with a base station and three rover units. These data were corrected for positional errors using the National Geodetic Survey Online Positioning User Service (OPUS). The OhmMapper produced a grid of 21 resistivity sections, including 16 oriented east-west and 5 north-south. The ERI was used to collect 7 sections including 3 north-south, 1 east-west and 3 angled from northwest-southeast. One north-south and the one east-west ERI line overlapped an OhmMapper line, allowing the measured resistivities of the two methods to be compared.

The resistivity mapping was based on measuring the electrical properties of near-surface earth materials, which vary with grain size, pore-space saturation, the solute content of pore water and the electrical properties of the minerals. Generally, electrical current travels readily in solute-rich pore water and very poorly in air. Also, cations adsorbed to soil particle surfaces reduce resistivity. Clay particles have large surface area per volume and thus have generally lower resistivities (1 – 100 Ohm-m) than sands or gravels (10 – 800 Ohm-m), which are lower than limestone bedrock (50 – 100 Ohm-m) (McNeill, 1980). Carefully measuring the change in strength of a known electrical current over different known distances produces a profile of the varying resistance of the subsurface material. Although the wide range of resistivities for materials generally prevents determination of the actual subsurface material from resistivity alone, the patterns and positions of resistivity can be used to make an initial prediction about subsurface structures which can be tested later with additional data.

Installation of Piezometer Field

In the first study by Fuchs et al. (2009), fifteen piezometers were installed at various locations around a constant head trench with the majority of the piezometers located between the trench and the river. Several of these piezometers were utilized for this tracer injection study: piezometers A, C, D, I, J, N and P. In order to monitor potential tracer movement over much larger distances, additional piezometers were installed in the riparian floodplain (Figure 1). The piezometers were installed to a depth of approximately 5 m (17 ft) and were constructed of Schedule 40 PVC. Each consisted of a 3 m screened section at the base. The piezometers were installed using a using a Geoprobe (Kejr, Inc., Salina, KS) drilling machine. Piezometers 2, 4, 5, 9, 13, 33, and 34 in Figure 1 are located along the mapped preferential flow pathway. Twenty-four of the piezometers (i.e., piezometers 1-14, 16, 33-34, A, C, D, I, N, and J) and the trench were instrumented with automated water level loggers (HoboWare) to monitor water pressure and temperature at one minute intervals. Piezometers were surveyed to obtain the actual water table depth below ground surface. Stream stage data from a nearby USGS gaging station was used in the analysis. Two sampling points were also utilized to collect samples from the Barren Fork.

Injection Experiment

The trench constructed by Fuchs et al. (2009) was utilized in this research to induce a constant water head and a tracer source on the subsurface alluvial gravel with subsequent monitoring of flow and tracer transport in the piezometer field. The dimensions of the trench were approximately 0.5 m wide by 2.5 m long by 1.2 m deep. The bottom of the trench was located approximately 25 to 50 cm below the interface between the topsoil and gravel layers. A bracing system consisted of a frame constructed with 5 cm by 13 cm studs covered with 2 cm plywood. The top and bottom were left open to allow water to infiltrate directly into the gravel layer.

Prior to the injection, each piezometer and the Barren Fork were sampled and analyzed for background Rhodamine WT levels. Also, a water level indicator was used to determine the depth to the water table in each piezometer prior to injection. This provided a representation of the hydraulic gradient in the subsurface and a correlation between the water level and the pressure reading from the water level loggers. Next, water was pumped from the Barren Fork into the trench using two pumps at approximately 160 gallons per minute (0.010 m^3/s) in order to induce water movement. Pumping started at 11:36 AM on April 3, 2009. The steady-state water level in the trench was held as constant as possible at approximately 140 cm above the bottom of the trench. Pumping continued for approximately three hours prior to Rhodamine injection in order to reach pseudo-steady state flow conditions.

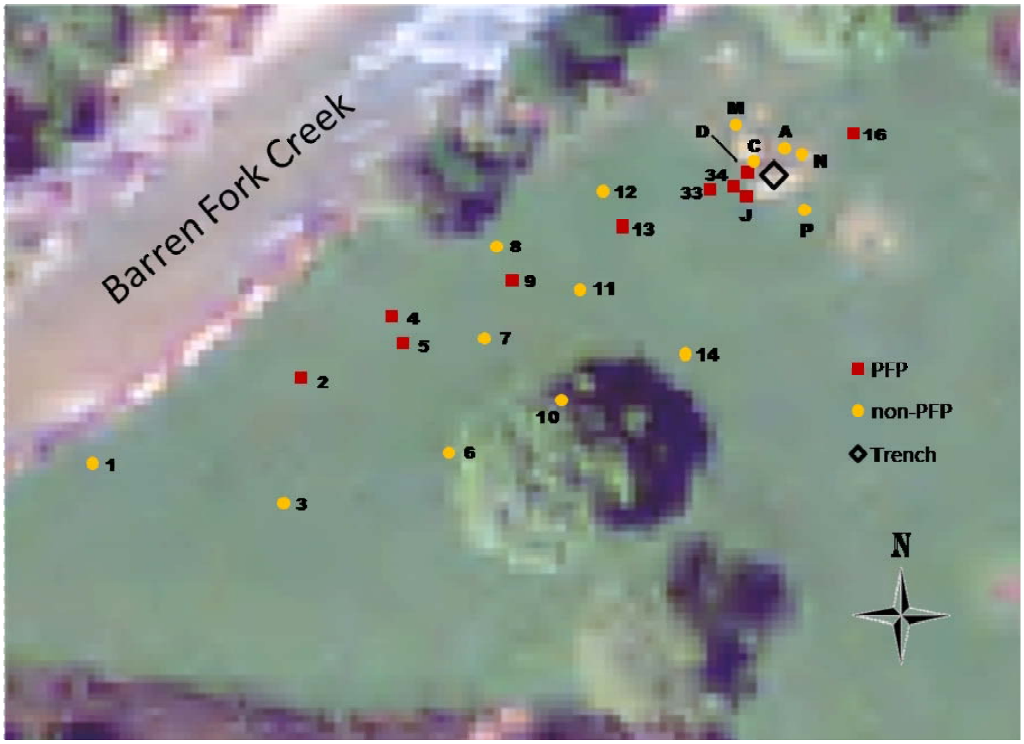

Figure 1. Aerial image of the Barren Fork field site with installed piezometers used for the current tracer injection study. Lettered piezometers were originally used by Fuchs et al. (2009); numbered piezometers were installed to monitor tracer movement from the trench system over larger distances.

Rhodamine WT was injected into the trench from 2:25 to 3:51 PM at a constant rate using a variable rate chemical pump to obtain a constant trench solution of 85 mg/L. Once the injection began, samples were taken from the piezometers, trench, and creek for the duration of the experiment in order to monitor the movement of the Rhodamine WT tracer. To sample the piezometers, a peristaltic pump was used with tubing at approximately 10 cm below the steady-state water level. Pumping ended around 9:30 PM.

Results and Discussion

Subsurface Mapping of the Riparian Floodplain

The grid of OhmMapper resistivity sections shows a series of low resistivity structures that lie roughly parallel to the existing stream channel separated by higher resistivity features (Figure 2). These can be interpreted as relict cut-off stream channels which were subsequently filled with fine sediments having low resistivity. The higher resistance areas between may represent gravel-dominated lateral or mid-channel bars. The Barren Fork, adjacent to the site, is a gravel-bed Ozark stream with prominent mid-channel and lateral gravel bars. The topography of the site is generally flat and level, but there are several similar linear depressions that coincide with the mapped low resistance areas.

The length of the OhmMapper sensor array precluded collecting resistivity data close to the existing well field. The ERI lines could be placed within the well field and those lines were used to attempt to locate the PFP. The wells affected by the PFP discovered in the original pumping test (Fuchs et al., 2009) were near a zone of high resistivity from the trench to the southwest (Figure 3). This linear trend is parallel to the trend shown by the low-resistivity features revealed by the OhmMapper lines, suggesting a common origin. The high resistivity indicates that the structure may be dominated by gravel and may create a direct hydraulic connection with the adjacent Barren Fork. An interesting feature suggested by the imaging was the apparent perching of the PFP above the shallow groundwater system, especially with distance away from the Barren Fork (Figure 3).

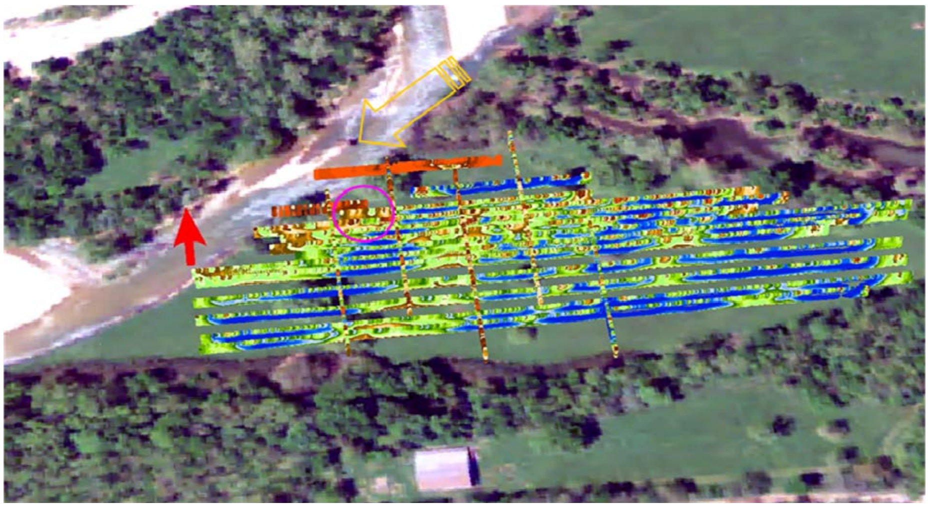

Figure 2: 3-D rendering of OhmMapper resistivity showing low resistivity (blue) structures. View is to the north (red arrow); Barren Fork is to the northwest of the image with the yellow arrow indicating the general flow direction. The location of the trench is identified with a circle.

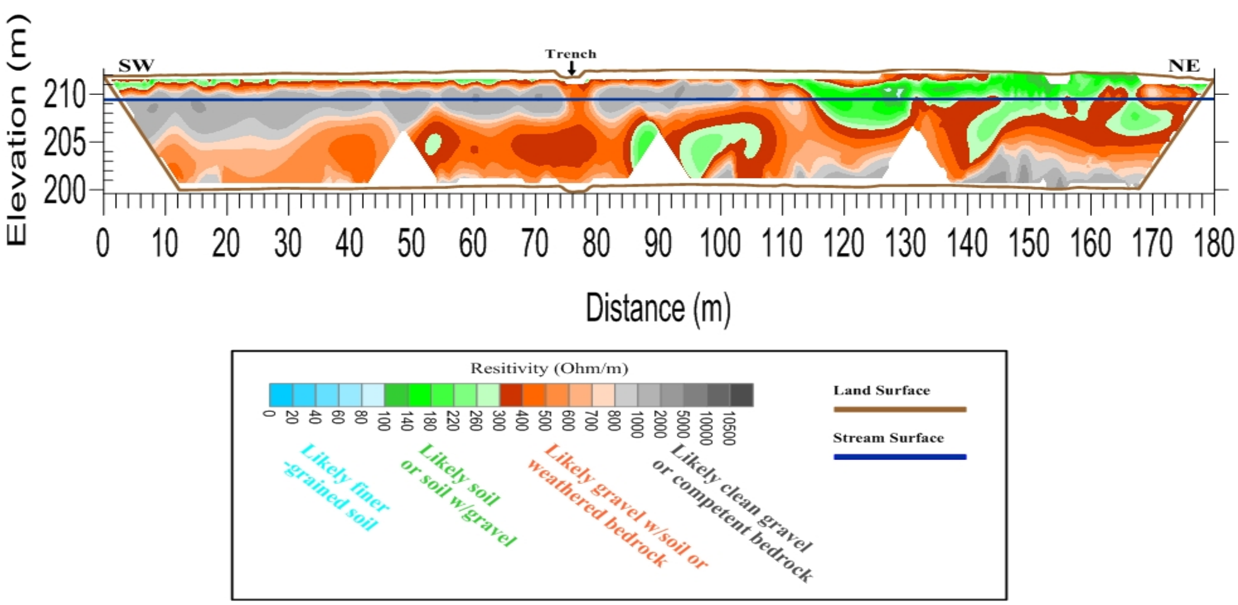

Figure 3: Composite ERI image running SW to NE along the hypothesized preferential flow pathway. The x-axis represents horizontal distance along the ground with the trench positioned at approximately 75 m, the y-axis is elevation above mean sea level. The color scale represents mapped electrical resistance. The line begins near piezometer 2 (Figure 1) and continues through the trench. The stream is approximately 5 m N of the SW end of the line, 20 m N of the trench and 60 m NW of the NE end of the ERI line. Stream flow is to the SW.

Injection Experiment

Water level measurements demonstrated that the stream was recharging the alluvial groundwater during the injection experiments (Figure 4). The flow gradient prior to injection was directed into the alluvial groundwater and downstream along the Barren Fork. The change in the water table during the injection (Figure 5) shows a mound in the shallow aquifer near the trench.

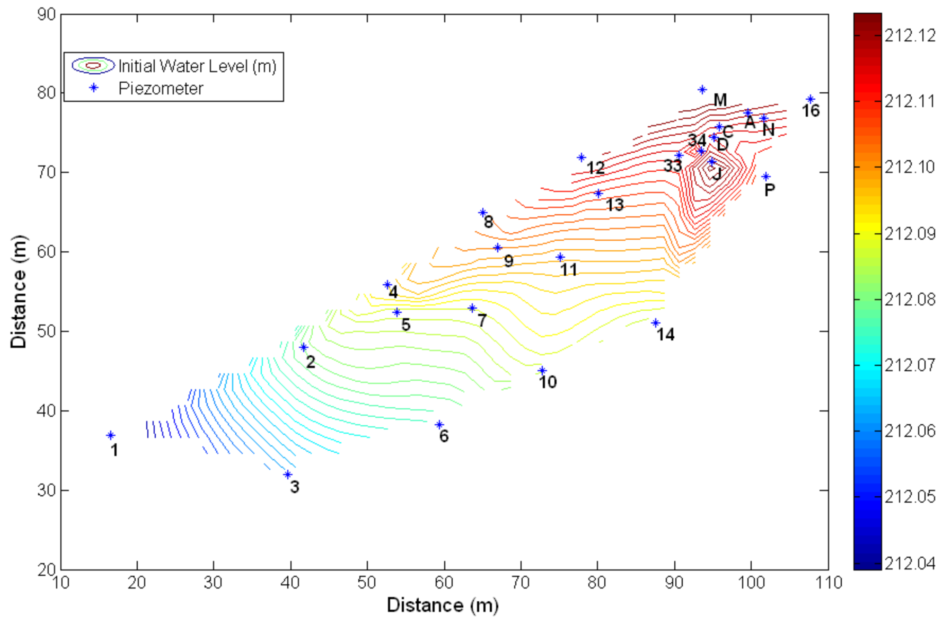

Figure 4. Water table elevations at 9:00 AM, before water injection into the trench.

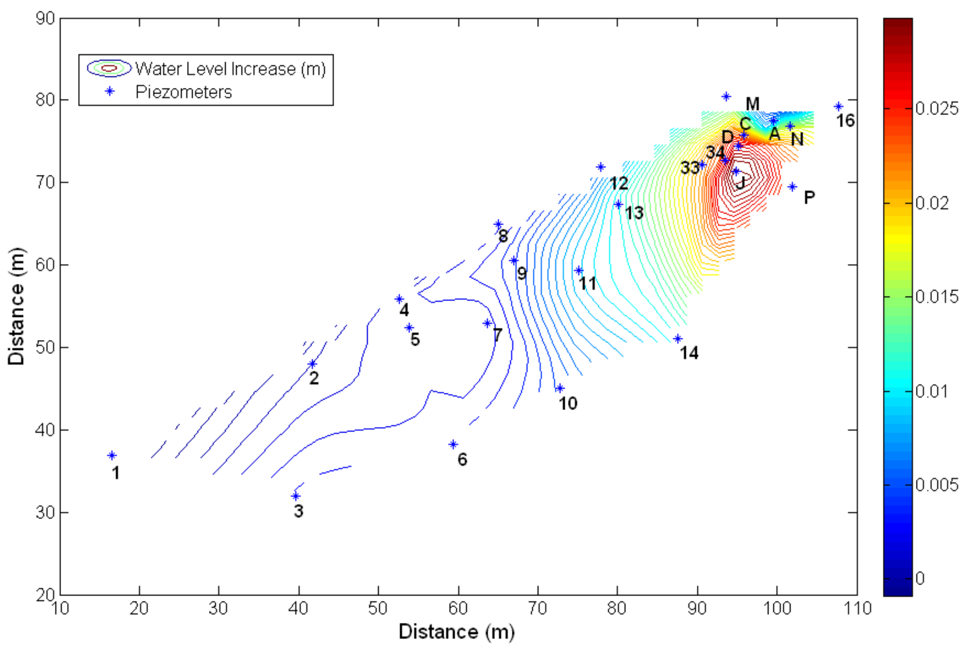

Figure 5. Change in water table elevation from 9:00 AM to 7:00 PM, after pseudo-steady state conditions due to water injection.

Since the PFP was above the water table, it was not active before pumping began. During the injection, it was hypothesized that water from the trench flowed through the perched preferential flow pathway and infiltrated into the alluvial groundwater system. In fact, manual water level sensors were not able to detect a specific water table elevation in piezometers D and J, hypothesized to be the result of perched water flowing laterally along the PFP and then dropping down the piezometer shaft.

Rhodamine WT concentrations induced in the trench were approximately 85 mg/L for a total time of 85 minutes (Figure 6). Concentrations in piezometer J located in the PFP and within 2 to 3 m of the trench mimicked concentrations in the trench, except for the concentration tail. Peak concentration in piezometers further downstream along the PFP (i.e., piezometers 34, 33, and 13) decreased with distance from the trench (Figure 6).

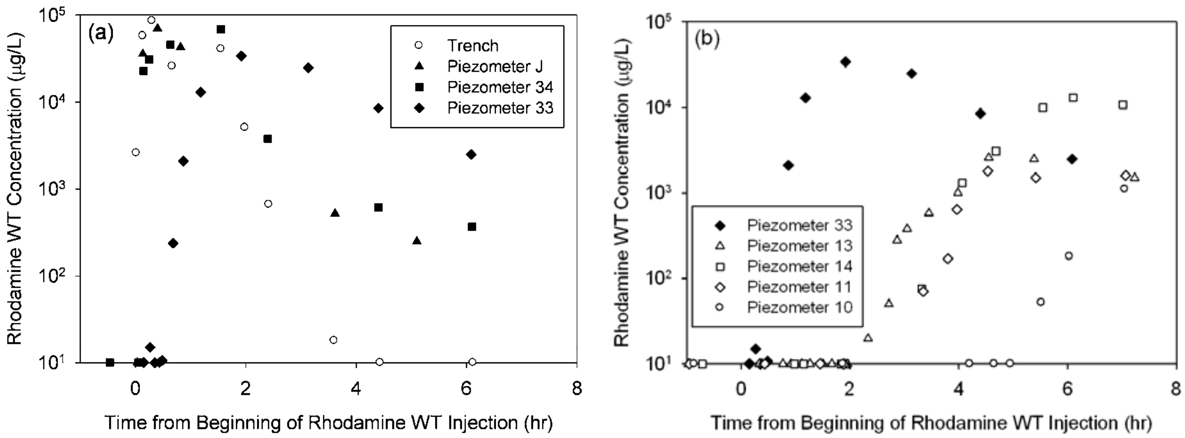

Figure 6. Rhodamine WT concentrations measured in the trench and piezometers during the injection experiments.

In piezometers 34, 33, and beyond, the Rhodamine WT had infiltrated through the gravel separating the PFP and alluvial groundwater. This Rhodamine WT was then transported according to local gradients in the groundwater system. In fact, Rhodamine WT was detected in piezometers outside of the PFP at relatively large concentrations (i.e., 1000 to 10,000 μg/L), but only on the side of the PFP away from the Barren Fork (Figure 6). No Rhodamine WT concentrations greater than 50 μg/L were observed in several piezometers, including those located immediately adjacent to the Barren Fork (i.e., 1-5, 7-9, 12, 16, and M). The injection experiment was conducted when the stage in the Barren Fork was approximately 30 to 60 cm above base flow levels. It was hypothesized and then verified based on the water level measurements (Figure 4) that the Barren Fork was recharging the alluvial groundwater, thereby pushing Rhodamine WT further away from the stream. The PFP when active may create a pathway to distribute contaminants to the alluvial groundwater along the length of the PFP and then movement may be driven by the interaction between the stream and alluvial groundwater.

An interesting result from the trench test was the observation of asymmetrical breakthrough curves for the Rhodamine WT concentrations in many of the piezometers. This asymmetrical breakthrough, with the tail of the curve remaining high, suggested that the system was largely influenced by physical heterogeneity at the macroscopic scale (i.e., 10^{-1} to 10^{1} m), a result that is not surprising based on the electrical resistivity mapping. As discussed by Brusseau (1998), the presence of smaller hydraulic conductivity zones most likely created locations in the flow field with little advective transport. Such domains act as source/sink areas and contribute mass to the advective domains (i.e., preferential flow pathway) over time. These results, combined with the observation of the stream recharging the groundwater, confirm the hypothesis of the alluvial groundwater acting as a transient storage zone.

Summary and Conclusions

This research identified the presence and demonstrated the impact of a preferential flow pathway on water and conservative tracer transport in a riparian floodplain system. The preferential flow pathway was mapped using electrical resistivity imaging and appeared to create a direct hydraulic connection between the Barren Fork and the subsurface of the riparian floodplain at a particular elevation in the subsurface. The tracer injection study demonstrated that the preferential flow pathway influenced the movement of the tracer and the distribution of tracer movement into the shallow groundwater system. The interaction between the Barren Fork and the alluvial groundwater then controlled the movement of the tracer in the shallow groundwater. The results verified the hypothesis of the alluvial groundwater acting as a transient storage zone as contaminants in the stream can be stored in the alluvial groundwater. The preferential flow pathway, perched above the shallow groundwater system, may not become hydrologically active except under high flow events. This is important, however, as high flow events usually contribute significantly to total contaminant loading in downstream water reservoirs. Additionally, the preferential flow pathways may become active during recharge between the surface and subsurface, affecting the distribution of material into the shallow groundwater system.

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